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VTOL TRANSPORT AIRCRAFT

FC Comparative Study

TRANSITION ANALYSIS OF THE VERTODYNE
VERTOL REPORT NO. R-79

VERTOL
Aircraft Corporation

formerly - Piasecki Helicopter Corporation

Comparative Study of Various Types of

VTOL Transport Aircraft

TRANSITION ANALYSIS OF THE VERTODYNE
REPORT R-79

Vertol Aircraft Corporation   Morton, Pennsylvania

ONR   **ARMY**

A Combined

Research and Development Program

Contract NONR 1681(00)

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I. SUMMARY

A preliminary analysis of transition is undertaken for the verto-dyne, a VTOL turbojet driven aircraft which employs ducted fans submerged in the wings for vertical lift. These fans are driven by a turbine powered by diverting the main jet exhaust. The analysis of the motion of this aircraft in going from the state where the weight is supported entirely by the fans, to the state as a jet-propelled airplane indicates the feasibility of such a scheme, even when the propulsion system is capable only of on or off operation in supplying power to the fans. The time required and the maximum accelerations to be experienced in reaching the normal airplane state appear to be reasonable. However, it is concluded that a more exact analysis of the problem should be performed considering in more detail the kinematics of the vertodyne. In addition, some study should be given to the inverse transition problem which would be encountered in landing.

II.   INTRODUCTION

The vertodyne is a VTOL, turbojet driven aircraft which
employs ducted fans submerged in the wings for vertical lift.   These
fans are driven from turbines powered by diverting the main jet exhaust.
A schematic diagram of this lifting-propulsion system is shown in
Figure 1.

The general concept of the vertodyne appears physically and
mechanically sound.   However, there are some specific problems concerned
with the operation of this type of aircraft which are in need of study.

This report considers the problem of transition in the vertodyne;
that is, of going from the hovering regime, where the weight of the
aircraft is supported entirely by the ducted fans, to the airplane
state where the weight is supported by the lift developed on the wing.
The purpose of this report is not to present a detailed analysis of
the problem, but rather to show from general considerations that
the transition is feasible.

III.   EQUATIONS OF MOTION

A sketch of the possible forces acting on the vertodyne at any instant are shown in Figure 2.   These forces are defined as:

T_F =   thrust per fan

T_j =   total jet thrust

L   =   lift developed by the wing

D   =   total drag

W   =   weight of aircraft

The various angles are defined as:

α =   angle of attack of wing zero lift line

ϕ =   angle between the fan thrust vector and the vertical y axis

δ =   angle between the zero lift line and the normal to the thrust vector

The direction of the thrust may be changed either by changing the trim of the entire ship or by deflecting the slipstream with the lower cowling shown in the diagram.   This cowling folds flush when the fan is not in use.

For this analysis only, the approximate equations of motion will be considered given by:

$$F_x = M\ddot{x} = T_j + BT_F \phi - D \tag{1}$$

$$F_y = M\ddot{y} = W - BT_F - L \tag{2}$$

where: M   =   mass of the aircraft

B   =   number of fans

These equations ignore any effect of the rotation of the ship or of the resultant velocity vector. In addition, ϕ is assumed to be a small angle.

Another equation of possible importance is the equation of motion of the fans since the inertia of the fans could continue to supply thrust for a period of time after the power has been removed and full jet thrust applied. It must also be considered in the case where the power is gradually removed from the fans with a corresponding increase in the jet thrust. The equation of motion for each fan is:

$$I \dot{\omega} = Q_S - Q_A$$

where: I = fan polar moment of inertia

ω = angular velocity of fan

Q_S = shaft torque tending to rotate fan

Q_A = aerodynamic torque opposing rotation of fan

IV.   TRANSITION ANALYSIS

Consideration of typical values of the fan characteristics for the vertodyne, as will be shown later, has indicated that upon removal of power from the fans, the angular velocity of the fan, as calculated from equation (3) will decrease rapidly.   Thus, during transition one should contemplate only on the thrust available from the fans under a constant power. This fact is significant for if the power system is designed as purely an on-off system then the airplane should be in a normal flying state before cutting the power to the fans. In other words, the lift coefficient of the wing in combination with the velocity of the aircraft, at the instant of switching the power, should be capable of supporting the weight of the aircraft.

The purely on-off power switching system is the only one which will be considered here since it is mechanically the simpler one. If transition can be accomplished with this system in a smooth fashion, then it can obviously be accomplished with a system which gradually removes the power from the fans while increasing the jet thrust.

In beginning transition from the hovering state, the thrust vector would be tilted forward. The aircraft would probably be trimmed to $C_L = 0$ in order to avoid induced drag and thereby reduce the time required to build up to a given speed. Since the thrust of the fans is supporting the weight of the ship during this period, the maximum acceleration is obviously

$$\ddot{x}'_{max} = \phi g \tag{4}$$

T_j is zero so that the time required to reach a given velocity is obtained by integrating equation (1) with D being simply the total drag at $C_L = 0$ and with BT_F equal to the weight.

$$\dot{V}_x = g \left[\phi - \frac{1}{2} \rho \ \frac{S_w}{W} \ C_{D_o} \ V_x^2 \right] \tag{5}$$

or

$$V_x = \sqrt{\frac{2 W \phi}{\rho \ S_w \ C_{D_o}}} \left[\frac{\exp\sqrt{\dfrac{2 \rho \ S_w \ C_{D_o} \ \phi g}{M}} \ t - 1}{\exp\sqrt{\dfrac{2 \rho \ S_w \ C_{D_o} \ \phi g}{M}} \ t + 1} \right] \tag{6}$$

where: S_w = wing area

C_{D_o} = total drag coefficient for $C_L = 0$

$V_x = \dot{x}$

It will be seen later for a typical vertodyne that the value of t required to reach flying speed is reasonably short.

After reaching a satisfactory speed, the angle α must be increased before cutting off the power to the fan. However, during this time the angle ϕ should not be decreased to any extent. A numerical integration of this part of the transition for a typical vertodyne showed that if the angle ϕ was decreased by the same rate as the increase of α , the loss in the forward component of thrust coupled with the increased drag reduced the forward velocity of the aircraft to such an extent that at no time was the lift coefficient and velocity sufficient to support the weight of the aircraft. This leads to the important conclusion that some provision must be made for tilting the thrust vector of the fans independent of the wing angle.

Consider the relationship between the angles ϕ and α which must hold in the steady case if, at the instant of cutting the fan power, the lift of the wing is to be sufficient for supporting the weight of the aircraft. For a given velocity the lift coefficient of the wing must be:

$$C_L = \frac{W}{\frac{1}{2} \rho V_x^2 S_w} \tag{7}$$

But under steady conditions, the velocity V_x is obtained from equation (5) as

$$V_x^2 = \frac{\phi W}{\frac{1}{2} \rho S_w C_D} \tag{8}$$

where C_D is now the total drag coefficient including the induced drag. Substituting this in equation (7) gives the simple result:

$$\phi = \frac{C_D}{C_L} \tag{9}$$

Since the ratio C_D/C_L is a function of α, equation (9) is the necessary relationship between ϕ and α. Of course, equation (9) is very conservative since, if the wing were developing a lift equal to the weight at the same time as the fan, the aircraft would experience a one g acceleration upward. In actual practice, the pilot would probably cut the power to the fan slightly before reaching the condition given by (8).

V.   APPLICATION OF RESULTS TO A TYPICAL VERTODYNE

The following characteristics are estimated for a typical
large vertodyne:

$$W \quad = \quad 112,000 \text{ lbs.}$$

$$T_j \quad = \quad 40,000 \text{ lbs. maximum}$$

$$B \quad = \quad 2$$

$$a_o \quad = \quad 4.27 \, C_L/\text{radian}$$

$$I \quad = \quad 1250 \text{ slug - ft.}^2$$

$$Q_{s_o} \quad = \quad 150,000 \text{ ft. - \#/fan}$$

$$AR \quad = \quad 4.9$$

$$\omega_o \quad = \quad 108 \, \frac{\text{rad.}}{\text{sec.}}$$

$$C_{d_o} \quad = \quad .0692 \text{ with shroud down}$$

$$S \quad = \quad 2284 \text{ ft.}^2$$

For $Q_s = 0$ equation (3) can be integrated assuming the
aerodynamic torque to be proportional to ω^2. If this is done, the
following is obtained:

$$\frac{\omega}{\omega_o} = \frac{1}{1 + \dfrac{Q_{s_o}}{I \omega_o} t} \tag{10}$$

where:
$$\omega_o = \omega \quad at \quad t = 0$$

Equation (1) is plotted as a function of t in Figure (3)
for this typical vertodyne to illustrate the rapidity with which the
fan angular velocity decreases. Since the thrust delivered by the fan
would be approximately proportional to ω^2, the ratio (ω / ω_o)^2
is also plotted in Figure (3). If at the time of cutting the power,

the total thrust is equal to the weight of the aircraft, the curve
$(\omega/\omega_o)^2$ is simply the ratio of the thrust to the weight.

The angle ϕ , the angle necessary for cutting the power to
the fan, is given in Figure 4. This angle in radians, according to
equation (9), is the ratio C_D/C_L. The angle δ , which is the sum
of ϕ and α , is also given in Figure (4). From the standpoint
of mechanical simplicity, the angle δ should be as small as possible.
This is seen to occur at an α of between 8° and 10°. Thus, for this
aircraft the thrust vector would have to be capable of being tilted
relative to the normal to the zero lift line of the wing, to an
angle of approximately 23°. For this value of δ , ϕ and α would be
approximately 13° and 10° respectively.

The value of ϕ used to accelerate would be approximately
18°. At this angle it would require 31.6 seconds, according to
equation (6), to reach the steady speed of 236 fps corresponding to
a ϕ of 13° as calculated from equation (8).

VI.   CONCLUSIONS AND RECOMMENDATIONS

The exact analysis of the transition phase of a vertodyne will require a more complete knowledge of the capabilities of the propulsion system. However, the preliminary considerations given in this report indicate the feasibility of transition from the powered fan to the jet-propelled state, even if the propulsion system is only capable of switching rapidly from one state to the other.

The best method of transition appears to be as follows. The vertodyne is first brought up to speed from hovering by tilting the thrust vector of the fans. During this phase the aircraft is trimmed with the wing at a zero angle of attack. Upon reaching a certain velocity, the angle of attack is increased while maintaining a forward inclination of the thrust vector. Upon reaching a sufficient angle of attack, the power to the fans is removed and the jet thrust applied.

The time required to build up a velocity sufficient for transition for a typical, large vertodyne is of the order of 32 seconds. During this time a maximum acceleration of 10 ft. per sec.^{2} would be experienced. In order to effect a transition with no loss in altitude, this analysis indicates that it will be necessary to provide some means of tilting the thrust vector of the fans independent of the wing angle. This can probably be accomplished by deflecting the slipstream of the fans.

The proverbial surface of the problem has only been scratched by this report. The performance possibilities of this type of aircraft are such that a more detailed and exact analysis of the transition phase should be undertaken. In addition to considering in more detail, the kinematics of the problem, the inverse problem of transition during landing should be studied.
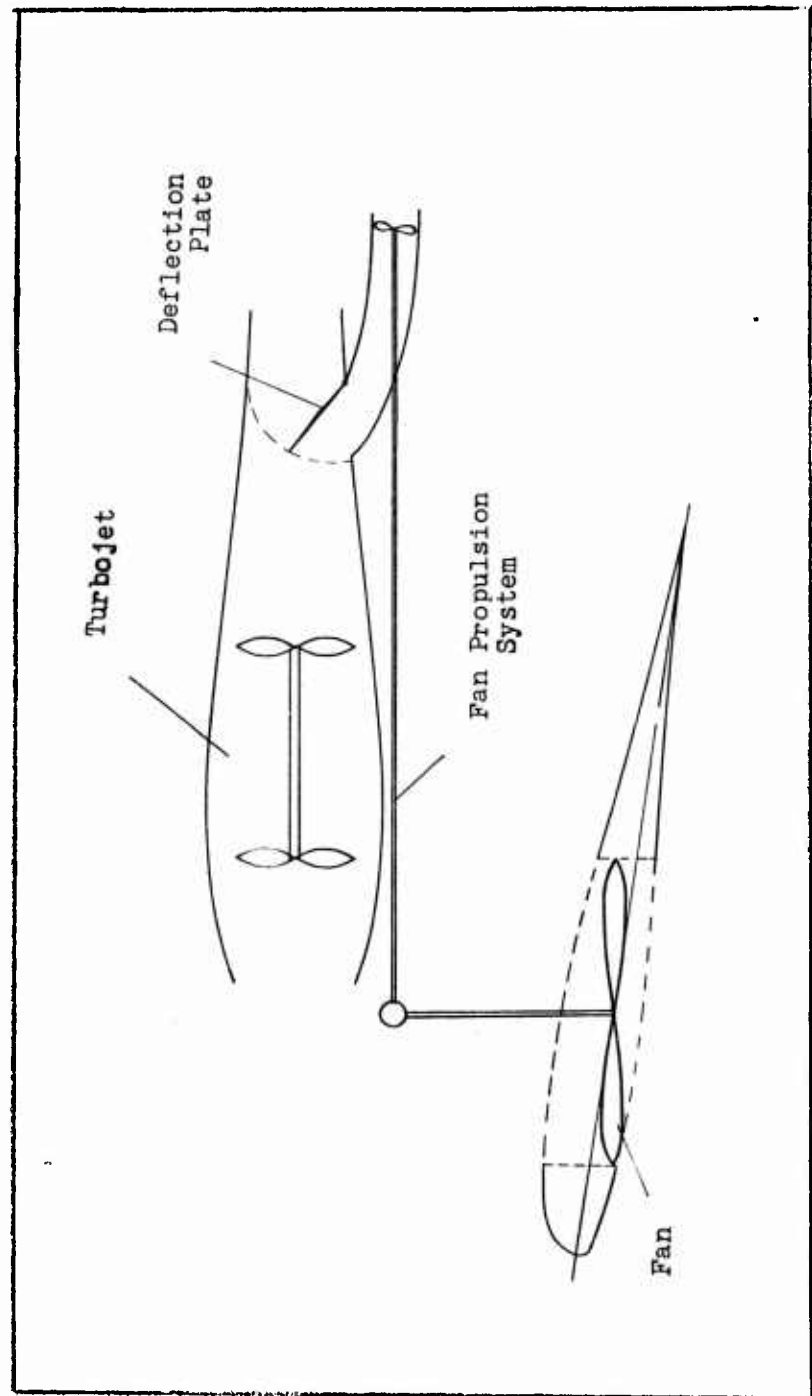
FIGURE 1

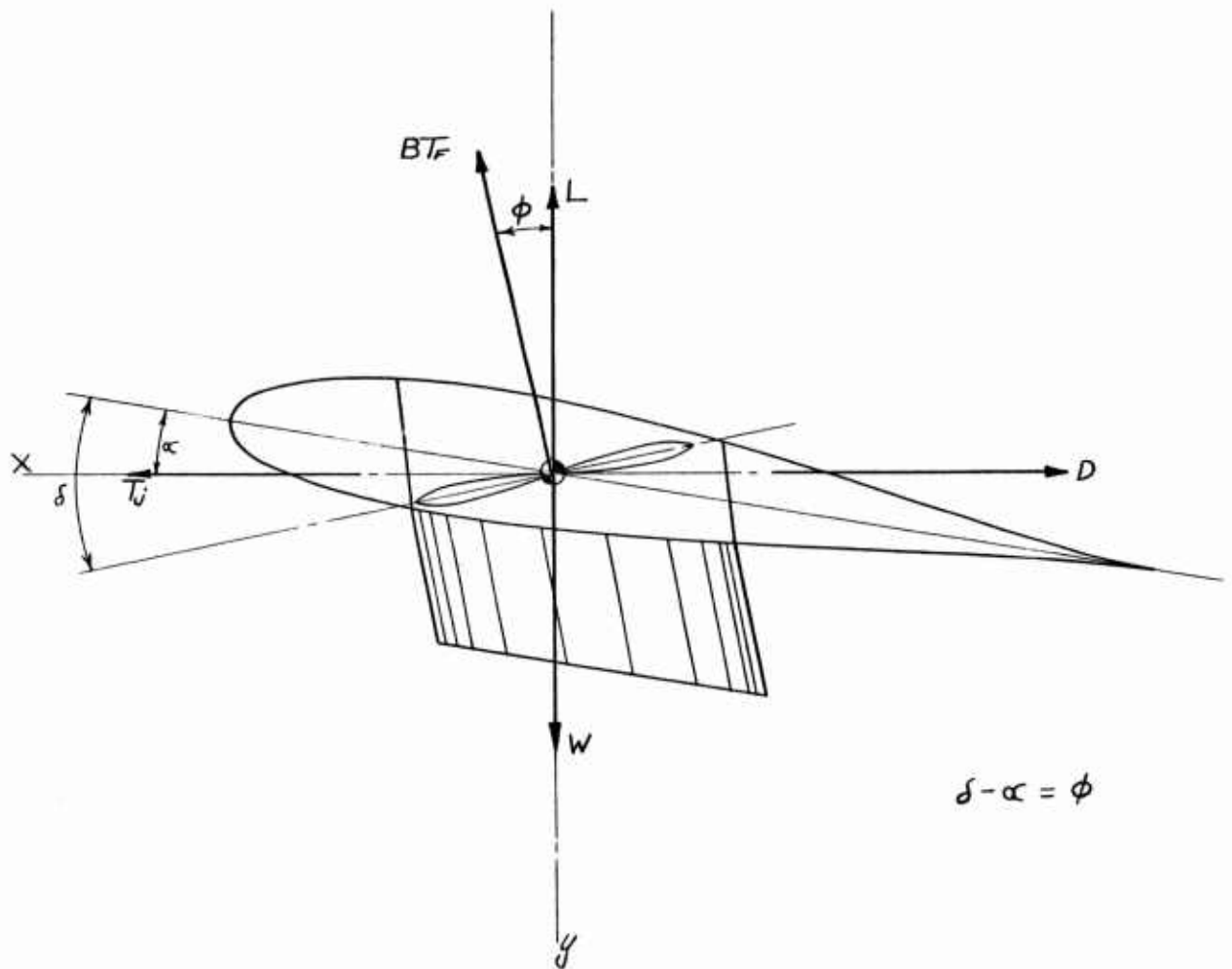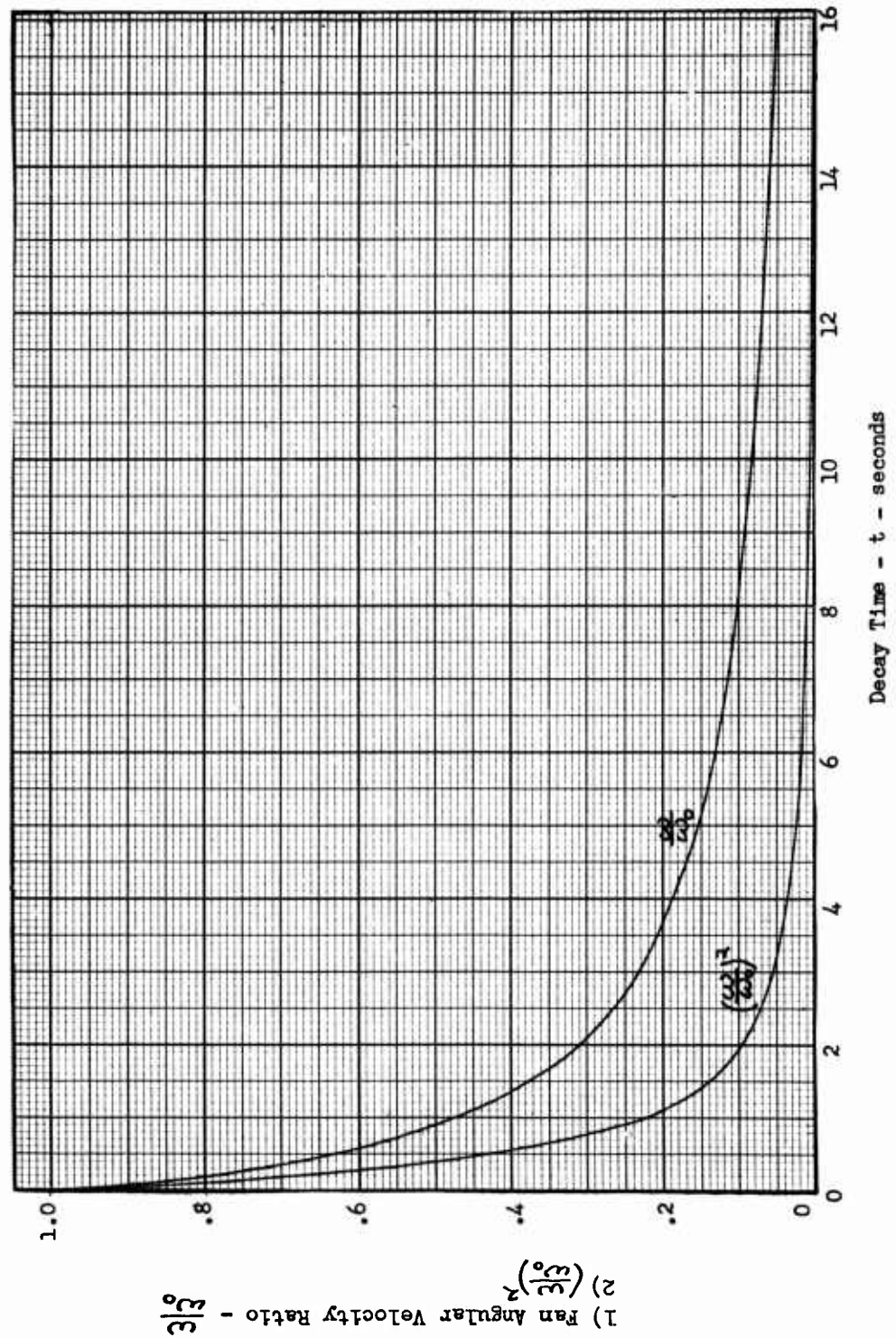LIFTING – PROPULSION SYSTEM

FIGURE 2

GENERAL FORCE DIAGRAM

$$\delta - \alpha = \phi$$

FIGURE 3

FAN ANGULAR VELOCITY RATIO AND
RATIO SQUARED VS. DECAY TIME
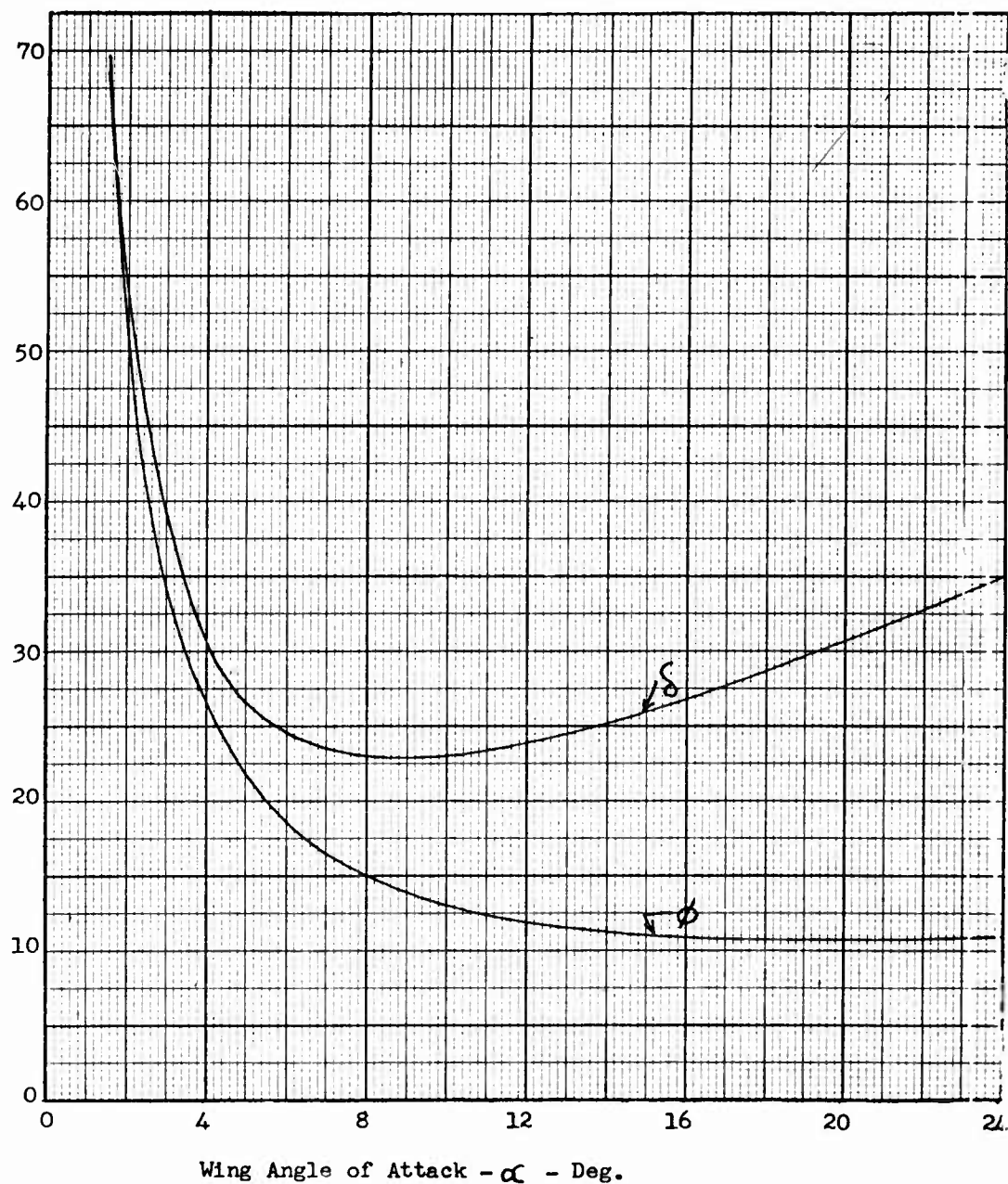
FIGURE 4

FAN THRUST VECTOR ANGLE; AND SUM OF FAN THRUST VECTOR ANGLE
AND WING ANGLE OF ATTACK VS. WING ANGLE OF ATTACK

1) Fan Thrust Vector Inclination - ϕ - Deg.
2) $\delta = \phi + \alpha$ - Deg.

Wing Angle of Attack - α - Deg.